

Axigluon as Possible Explanation for $p\bar{p} \rightarrow t\bar{t}$ Forward-Backward Asymmetry

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Abstract

A flavor-nonuniversal chiral color model is introduced. It is used for comparison to the recent data on $p\bar{p} \rightarrow t\bar{t}$. We concluded that the data are consistent with interpretation as an axigluon exchange within 1σ and a unique rise and fall behavior is predicated with regard to the asymmetry A_{FB}^t as a function of $t\bar{t}$ invariant mass, which can distinguish our model from others before one discovers the axigluon resonance. Further aspects of the model are discussed.

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I. INTRODUCTION

Since it underlies nuclear physics and hadronic physics, it is important to understand whether the standard version of the theory of strong interactions, quantum chromodynamics (QCD), is an adequate description at much higher energies. For example, although electroweak interactions exhibit parity violation, QCD theory as presently formulated respects parity conservation.

One generalization of QCD proposed some time ago is chiral color [1, 2] in which the color gauge group arises from the spontaneous breaking of a larger group at higher energy. This gives rise to a massive color octet of gauge bosons, axigluons, which acquire mass through the Higgs mechanism. The earliest chiral color models treated the different quark flavors universally. A flavor-nonuniversal version which, however, involved extension of the electroweak gauge group was discussed in [3]. In the present article we introduce a new flavor-nonuniversal chiral color model in which the electroweak symmetry is unchanged from the standard model, thus is more conservative, and seek within it a unique experimental signature below the energy of the axigluon resonance.

One possible relevant experiment concerns the study of heavy quark asymmetries. Both CDF and D0 at Tevatron have observed large forward-backward asymmetry values in top anti-top pair events (A_{FB}^t) [4–6]. The latest measurement of A_{FB}^t is from the CDF experiment where they obtained:

$$A_{FB}^t = 0.193 \pm 0.065_{\text{stat.}} \pm 0.024_{\text{syst.}} \quad (1)$$

in the lab frame with 3.2 fb^{-1} integrated luminosity data [4]. Within the standard model (SM), the next-to-leading-order (NLO) QCD interference effects predict $A_{FB}^t(\text{SM}) = 0.051$ [8–10] and it is stable with respect to the QCD threshold resummation [11]¹. This is not enough to account for the measured large asymmetry and suggests there might be new physics in the top quark sector.

There have been several new physics proposals trying to explain this large positive asymmetry. However, any model trying to explain the large asymmetry encounters a challenge as it must also avoid predicting large deviation in total cross section $\sigma_{t\bar{t}}$ and $t\bar{t}$ invariant

¹ In the $t\bar{t}$ +jet production, however, a large cancellation of the top forward backward asymmetry occurs from NLO corrections [12].

mass $M_{t\bar{t}}$ since they are in good agreement with the SM predictions². One category of model suggests new physics in the t -channel with large flavor violating ut or dt couplings. Phenomenologically viable examples include t -channel Z'/W' exchange with large flavor violating couplings [13, 14], t -channel flavor and fermion number violating scalar as $SU(3)_C$ triplet or sextet[?]. Nevertheless, it is difficult to imagine how such *ad hoc* couplings can be naturally generated.

Another category of model involves vector bosons in the s -channel with chiral coupling to the light quarks and the top quark. A color octet particle is preferred in order to use its large QCD interference effect. $\sigma_{t\bar{t}}$ and $M_{t\bar{t}}$ also constrain the mass of the resonance. The top forward-backward asymmetry requires that parity transformation is violated if we apply it to the final top quark pair. Similarly, parity transformation applying to the initial light quark pair must also be violated which can be easily seen with an additional 180 degree rotation along the scattering plane. Since the QCD interactions already provide the vector couplings for the interference, a spin one, color octet with nonzero axial couplings is the basic requirement.

Such a new particle can be realized within a wide class of theories, invoked for phenomenological reasons [2] inspired by the weak interactions, used to explain the electroweak symmetry breaking [16], or motivated by study of extra dimensions [17, 18]. It has previously been observed by Ref. [19] that only the $g_A^q g_A^t < 0$ case gives rise to a positive asymmetry from interference and we pursue that here. In this paper, we consider a simple extension of the chiral model involving a fourth family and based on only two extra parameters to explain the observations. It leads to a striking prediction for a *rise and fall* behavior of A_{FB}^t as a function of $M_{t\bar{t}}$ as one approaches the axigluon resonance.

II. CHIRAL COLOR WITH A FOURTH FAMILY

We consider a chiral color model based on gauge group $SU(3)_A \times SU(3)_B \times SU(2)_L \times U(1)_Y$ with gauge couplings g_A , g_B , g_L and g_Y respectively. In this model, quarks of opposite chiralities are charged under different $SU(3)$ gauge groups. Similarly, quarks with the same chiralities but between the first two generations and the third and fourth generations (for

² We notice that the $t\bar{t}$ invariant mass $M_{t\bar{t}}$ distribution measured at the Tevatron is slightly softer than SM prediction.

reviews, see *e.g.*[21])³ are charged under different $SU(3)$ gauge groups. There is a bi-triplet scalar field Σ which gets a vev at the TeV scale $\langle \Sigma_{i\bar{k}} \rangle = u\delta_{i\bar{k}}$ and breaks the $SU(3)_A$ and $SU(3)_B$ to the diagonal subgroup, the QCD color group $SU(3)_c$. The SM Higgs scalars are now split into two parts, the quarkonic Higgs H_q which is a triplet under color groups $SU(3)_A$ and $SU(3)_B$ and the leptonic Higgs H_l which is a singlet under color groups. The full field contents are summarized in Table I.

Field	Q_i	u_i^c	d_i^c	Q_j	u_j^c	d_j^c	Σ	H_q	L_k	e_k^c	H_l
$SU(3)_A$	3	1	1	1	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	3	3	1	1	1
$SU(3)_B$	1	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	3	1	1	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	1	1	1
$SU(2)_L$	2	1	1	2	1	1	1	2	2	1	2
$U(1)_Y$	1/3	-4/3	2/3	1/3	-4/3	2/3	0	1	-1	2	1

TABLE I: Charge assignment of all the quark, lepton fields and the Higgs fields under $SU(3)_A \times SU(3)_B \times SU(2)_L \times U(1)_Y$. The flavor indices are as $i = 1, 2$, $j = 3, 4$ and $k = 1, 2, 3, 4$. The hypercharge is defined as the convention of electric charge $q = I_L^3 + Y/2$ where I_L^3 is the third component of $SU(2)_L$ isospin. All the $SU(2)_L$ singlet fields are defined in their conjugate forms.

The kinetic term for the link field becomes the mass term for the massive gauge boson $\text{Tr}[(D_\mu \Sigma)^\dagger (D_\mu \Sigma)] \supset u^2 (g_A A_\mu - g_B B_\mu)^2/2 = u^2 g^2 (G_\mu^1)^2/2$, where $g \equiv \sqrt{g_A^2 + g_B^2}$. The rotation matrix between gauge bosons in mass eigenstates and gauge eigenstates is

$$\begin{pmatrix} G_\mu^1 \\ G_\mu^0 \end{pmatrix} = \begin{pmatrix} s_g & -c_g \\ c_g & s_g \end{pmatrix} \begin{pmatrix} A_\mu \\ B_\mu \end{pmatrix}, \quad (2)$$

where we define $s_g \equiv \sin \theta \equiv g_A/g$ and $c_g \equiv \cos \theta = g_B/g$ so $\theta = \arctan(g_A/g_B)$. The massless field G_μ^0 is the usual QCD gluon while we call the massive octet vector boson G_μ^1 “axigluon”.

The QCD couplings are flavor universal as $g_s = g s_g c_g$. There is a redundant symmetry of the model $g_A \leftrightarrow g_B$, so only half of the parameter space in θ is physical ($\theta \leftrightarrow 90^\circ - \theta$). Requiring that our model is perturbative $g_A, g_B < 2\pi$ we impose a further constraint $10^\circ <$

³ At the low energy, the fourth generation appears as a Wess-Zumino-Witten term, which introduces one-loop suppressed counter terms among the massive octet gauge boson and QCD gluon.

$\theta < 45^\circ$. For the fermions charged under gauge group $SU(3)_A$ and $SU(3)_B$, their couplings to the massive axigluon G_μ^1 are gs_g^2 and $-gc_g^2$ respectively. Therefore, the vector and axi-vector coupling strengths are

$$g_V^q = g_V^t = -\frac{gc_{2g}}{2}, \quad -g_A^q = g_A^t = \frac{g}{2} \quad (3)$$

where $c_{2g} \equiv \cos(2\theta)$. We can see that the axial-vector couplings are always nonzero and the above coupling strengths satisfy the following relations

$$g_A^q g_A^t < 0, \quad g_V^q g_V^t > 0 \quad \text{with} \quad g_V < g_A, \quad (4)$$

which are crucial for the phenomenology predictions below.

III. FORWARD-BACKWARD ASYMMETRY

The $V - A$ structure in axigluon interaction will induce parity violation in $q\bar{q} \rightarrow t\bar{t}$ and consequently a non-vanishing forward-backward asymmetry occurs in such process at the $p\bar{p}$ collider. To see this feature analytically, in Eq. (5), we give the matrix element square for $q\bar{q} \rightarrow t\bar{t}$ of the two leading production channels as the s -channel gluon and axigluon. γ/Z contribution do not interfere with the gluon diagram and are very small thus can be neglected.

$$\begin{aligned} \sum |\mathcal{M}|^2 = & g_s^4(1 + c^2 + 4m^2) \\ & + \frac{2g_s^2\hat{s}(\hat{s} - M_G^2)}{(\hat{s} - M_G^2)^2 + M_G^2\Gamma_G^2} [g_V^q g_V^t (1 + c^2 + 4m^2) \\ & + 2g_A^q g_A^t c] + \frac{\hat{s}^2}{(\hat{s} - M_G^2)^2 + M_G^2\Gamma_G^2} [((g_V^q)^2 + (g_A^q)^2) \\ & \times ((g_V^t)^2(1 + c^2 + 4m^2) + (g_A^t)^2(1 + c^2 - 4m^2)) \\ & + 8g_V^q g_A^q g_V^t g_A^t c] , \end{aligned} \quad (5)$$

where $m = m_t/\sqrt{\hat{s}}$, $\beta = \sqrt{1 - 4m^2}$ is the velocity of the top quark and $c = \beta \cos \theta$ where θ is the polar angle of the top quark with respect to the incoming up quark in the parton center-of-mass frame.

The asymmetry A_{FB}^t can be defined using the total number of top quark in positive and negative semi-sphere as

$$A_{FB}^t = \frac{N_t(\eta \geq 0) - N_t(\eta \leq 0)}{N_t(\eta \geq 0) + N_t(\eta \leq 0)}, \quad (6)$$

where η is the rapidity of the top quark. Under CP transformation, there also exists an equivalent definition by changing $N_t(\eta \leq 0)$ to $N_{\bar{t}}(\eta \geq 0)$. We can qualitatively see the asymmetry behavior from the linear term $(1 \pm \cos\theta)$ in the matrix element squared where $(1 + \cos\theta)$ corresponds to the maximal positive asymmetry. Equation (5) shows the correlation between $\cos\theta$ and the relative signs of the couplings. The contribution to A_{FB}^t due to the interference term depends on the sign of $g_A^q g_A^q$. The new physics contribution depends on the sign of $g_V^q g_V^t g_A^q g_A^t$. The key prediction of our model is that $g_V^q = g_V^t$ while $g_A^q = -g_A^t$. Therefore, both $g_A^q g_A^q$ and $g_V^q g_V^t g_A^q g_A^t$ are negative and the interference term induces a positive asymmetry while the new physics term induces a negative asymmetry below the resonance. Since most the events are far below resonance, the interference term completely overwhelms the new physics term when counting the overall A_{FB}^t . Nevertheless, at higher $M_{t\bar{t}}$ invariant mass, we may expect a competition between the interference term and the new physics term to provide an interesting signature to distinguish our model.

IV. NUMERICAL RESULTS

The SM prediction of $\sigma_{t\bar{t}}$ is in good agreement with measurements from CDF 4.6 fb⁻¹ luminosity data [22]

$$\sigma^{CDF}(t\bar{t}) = 7.50 \pm 0.31_{\text{stat}} \pm 0.34_{\text{syst}} \pm 0.15_{\text{Z theory}} \text{ pb} , \quad (7)$$

where the top quark mass is assumed to be 172.5 GeV. This CDF result is consistent with measurements from D0 [7] that use smaller data sets. We combine different errors in quadrature and obtain $\sigma^{exp} = 7.50 \pm 0.48$ pb.

The $t\bar{t}$ invariant mass distribution was also measured recently by CDF [23], the data from the last bin which are expected to give the most stringent constrain on our model are

$$\begin{aligned} \frac{d\sigma}{dM_{t\bar{t}}}(0.8 - 1.4 \text{ TeV}) = \\ 0.068 \pm 0.032_{\text{stat.}} \pm 0.015_{\text{syst.}} \pm 0.004_{\text{lumi.}} \text{ fb/GeV} . \end{aligned} \quad (8)$$

We combine different errors in quadrature as $d\sigma/dM_{t\bar{t}}(0.8 - 1.4 \text{ TeV}) = 0.068 \pm 0.036$ (fb/GeV).

Our simulation is only a leading order calculation. To fit the total cross section, we have multiplied by a NLO K -factor as $K = 1.329$ for $m_t = 172.5$ GeV. To be consistent

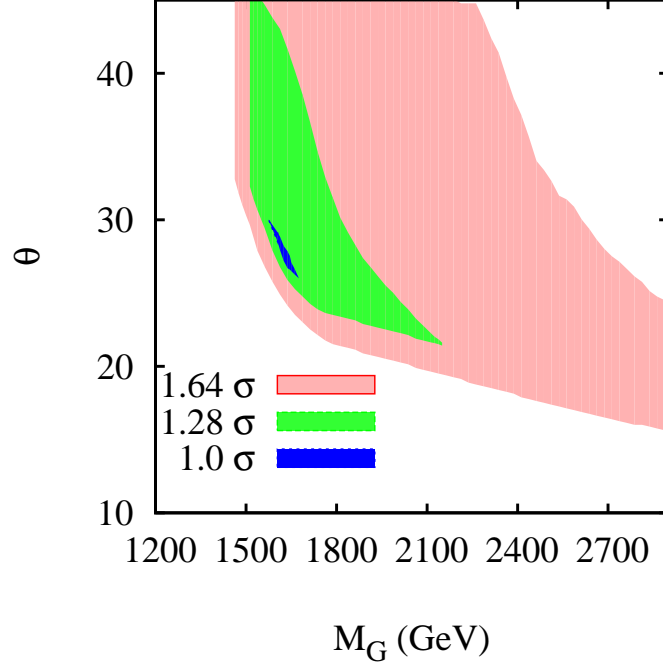


FIG. 1: Contour plot for 1σ , 1.28σ and 1.64σ allowed parameter space in the $\theta - M_G$ plane.

with measurements, the A_{FB}^t and $M_{t\bar{t}}$ results are based on simulation using $m_t = 175$ GeV. However since QCD corrections often soften the $M_{t\bar{t}}$ at high value, we did not multiply any K factor for our simulated result of the last bin value in $M_{t\bar{t}}$. Taking into account all the above constraints, we scan the allowed parameter space in terms of the axigluon mass M_G and the mixing angle θ between gauge groups $SU(3)_A$ and $SU(3)_B$ in Fig. 1. The 1σ , 1.28σ (80% C.L.) and 1.64σ (90% C.L.) regions are labelled accordingly.

To test the competition effects, we propose to use the A_{FB}^t dependence on $\sqrt{\hat{s}}$ ($= M_{t\bar{t}}$). To illustrate this feature of our model, we choose a benchmark point within the 1σ region as $M_G = 1525$ GeV and $\theta = 27^\circ$. We plot (solid line) the A_{FB}^t vs. $M_{t\bar{t}}$ with $M_{t\bar{t}}$ integrated every each 150 GeV of $M_{t\bar{t}}$ in Fig. 2. One can see the competition in A_{FB}^t between two terms at different $M_{t\bar{t}}$ in Fig.2 and when $M_{t\bar{t}}$ is close to on-shell G^1 region, the new physics contribution begins to dominate over the interference term which bend over the curve and generate a negative asymmetry. For comparison, we plot (in dashed line) a case where $g_V^q = -g_V^t$ so the new physics term also generates positive asymmetry.

In other theoretical proposals and the QCD corrections [11], the A_{FB}^t induced by other types of s -channel new physics without the above competition or t -channel new physics

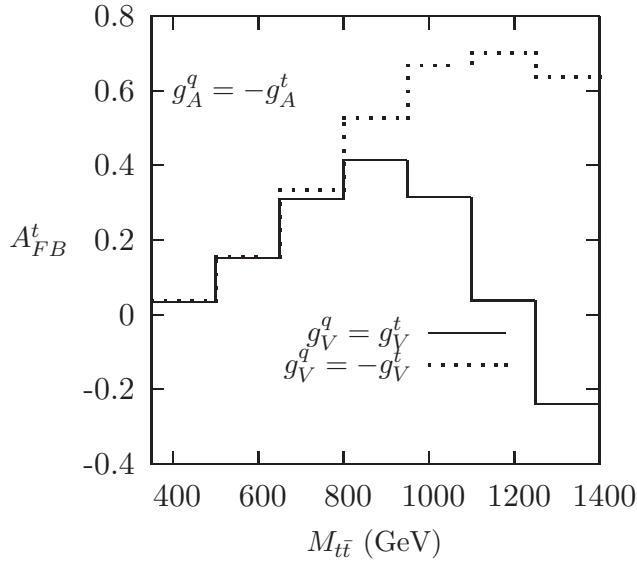


FIG. 2: A_{FB}^t vs. $M_{t\bar{t}}$ with $M_{t\bar{t}}$ integrated over each 150 GeV of $M_{t\bar{t}}$ using the benchmark point, $M_G = 1525$ GeV, $g_V^q = -0.577g_s$ and $g_A^q = -g_A^t = -1.155g_s$. The solid line corresponds to our model with $g_V^q = g_V^t$ and dashed line is a comparison plot with $g_V^q = -g_V^t$, as explained in the text.

[13] grows with $M_{t\bar{t}}$ which is very different from our prediction. When the A_{FB}^t vs $M_{t\bar{t}}$ distribution is available in the near future, it is then easy to confirm or rule out our model. This becomes crucial since the resonance is too heavy and cannot be directly produced at the Tevatron.

V. DISCUSSION

The above minimal setup can be extended to an extra dimension scenario on an interval bounded by left and right branes. We allow all fermions to propagate in the bulk and interactions to be determined through the five dimensional wavefunction overlap. In the spirit of deconstruction [25], one can imagine that the left-handed light quarks and the right handed top quarks are localized on the left brane while the right-handed light quarks and the left handed top quarks are localized on right one. The fourth generation is not needed in this case because the gauge anomaly will be cancelled among each generation [26]⁴. The

⁴ If all fermions are completely localized at the boundary brane, the gauge anomaly is not cancelled among each generation and one need the fourth generation or a $SU(3)$ Chern-Simons term in the bulk. In this case, one can use the path ordering of the Wilson line to generate the quark masses.

axigluon is the 1st KK gluon (g^1) whose wave function contains a node, and changes sign from one side of the extra dimension to the other. As a result the g^1 coupling for the left localized fermions has a minus sign relative to the one for the right localized fermions. Such a localization pattern guarantees Eqs. (4) which provide the essential requirements to fit the data and make the striking prediction. We expect that such a simple localization pattern can be embedded in different extra dimensional models [27, 28].

In this paper, we present a flavor-nonuniversal chiral color model to explain the Tevatron anomaly on top quark forward-backward asymmetry. The model predicts a heavy axigluon that couples to first two generation and third generation quarks with opposite axial couplings but same vector couplings with relative small sizes. The data are consistent with our model within 1σ for some parameters, and a large region of parameter space is found at 90% C. L. One can use A_{FB}^t vs $M_{t\bar{t}}$ distribution to further distinguish this model from other types of models that can explain A_{FB}^t anomaly before one discovers the axigluon resonance.

If the striking rise and fall behavior of A_{FB}^t vs $M_{t\bar{t}}$ were discovered, the implication is not only that strong interactions will violate parity at much higher energies as originally motivated Ref. [2], but Eqs. (4) suggest a possible specific pattern of parity violation.

VI. NOTES ADDED

After submission of our paper, we notice that the CDF collaboration measures the correlation between A_{FB}^t and $M_{t\bar{t}}$ by selecting events below or above $M_{t\bar{t}}$ edge point. To make a direct comparison with the CDF public result [24], we also plot A_{FB}^t vs $M_{t\bar{t}}$ edge distributions in Fig.3. This plot can be easily compared to the corresponding figure in [24].

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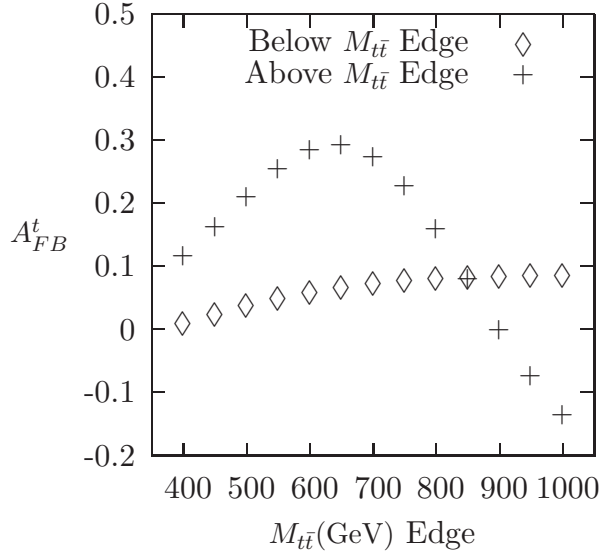


FIG. 3: A_{FB}^t vs. above/below $M_{t\bar{t}}$ edge using the benchmark point, $M_G = 1525$ GeV, $g_A^q = -g_A^t = -1.155g_s$ and $g_V^q = g_V^t = -0.577g_s$

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